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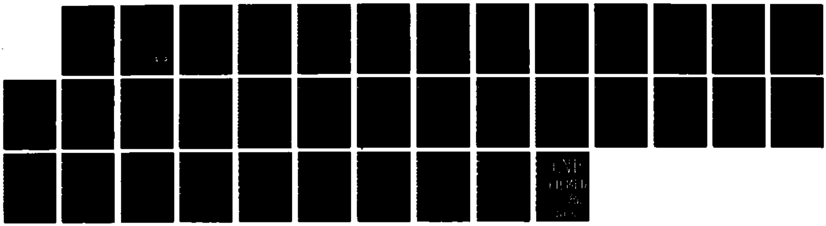

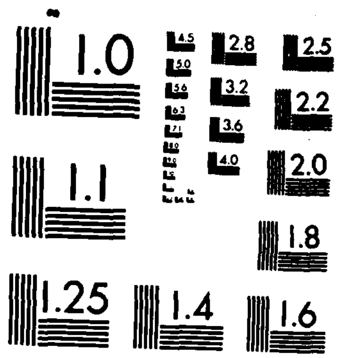

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INTERACTION OF IMAGE CHARACTERISTICS OF STEREOSCOPIC FORMS DURING DEPTH PERCEPTION

Robert Fox

Vanderbilt University

Nashville, Tennessee 37240

AD-A164 895

August, 1985

Final Report

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This report summarizes the results of a research program on the perceptual processing of relative depth information provided by stereoscopic displays formed from dynamic random element stereograms. Good agreement was found between the perceived depth position of stereoscopic targets with crossed disparity and those predicted from the geometry of stereopsis. The perceived depth positions were not compromised by the presence of potentially misleading cues to depth or by substantial reductions in the texture of the random element

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stereogram. Similar agreement between perceived and predicted depth was also found for a true three-dimensional display that permitted disparity to be held constant while viewing distance varied. But the depth positions of targets with uncrossed disparity were grossly underestimated with respect to the positions predicted by geometry, an outcome that is consistent with other evidence suggesting a functional difference between the processing of crossed and uncrossed disparity information. A reexamination of the concept of stereoanomaly suggests that its incidence may have been greatly overestimated by a specific method of testing, therefore, a decision to employ stereoscopic displays need not be conditioned on the assumption that operators would have to undergo special selection processes. A general conclusion supported by the results of the research program, in concert with other data, is that under unrestricted conditions of view, stereoscopic displays with crossed disparities convey veridical information about depth position.

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Per Dr. John J. O'Hare, ONR/Code 1142EP

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INTRODUCTION

The primary objective of this research program was to determine the degree of congruence between the apparent or perceived depth position of a stereoscopic form and the position predictable from the physical conditions of stimulation. This topic, which bears directly on the veridicality or validity of depth information presented in a stereoscopic or 3-D display, has been investigated previously under restricted laboratory conditions that yield results of limited generality. For that reason, the present inquiry was pursued under naturalistic conditions similar to those that would obtain during the routine operation of visual displays. To gain insights into potential interactions between depth position (X-axis) and stimulus configuration (X- and Y-axes), stereoscopic forms were created from dynamic random element stereograms continuously generated electronically. This approach precluded the occurrence of non-stereoscopic cues that can arise in conventional depth displays.

Keywords: afterimages; stereopsis; Visual perception

GENERAL APPROACH

In the majority of experiments, stimulus presentation and control was implemented by means of an optical-electronic system, developed at Vanderbilt University, for the continuous generation of random element stereograms. This system has been used in prior research on the

interaction of stereoscopic contours in visual space and has been described in detail previously (e.g. Shetty, Brodersen, & Fox, 1979) therefore only a brief description will be given here. But before proceeding to that description, it would be helpful to review quite briefly the basic attributes of a random element stereogram.

Random element stereograms, which were devised by Julesz (1960; 1971) consist of two matrices of randomly ordered elements or dots, with each matrix stimulating a separate eye. Under monocular or non-stereoscopic conditions of view, the matrices contain no perceivable edge or contour, with only the random elements being visible. If a subset of the elements in one matrix is displaced horizontally with respect to corresponding elements in the other matrix, such a displacement is not detectable under monocular conditions of view. But if the matrices are viewed stereoscopically, the binocular visual system automatically detects the displacement (retinal disparity) and produces a percept of a stereoscopic form with clear cut edges and a seemingly palpable surface located at some definite position in depth. Unlike the classic Wheatstone stereogram, which contains contours clearly discriminable under monocular conditions, contours in a random element stereogram are contingent upon the operation of stereopsis and have no independent physical existence. This fundamental difference, relative to conventional stereograms, has far-reaching implications for a number of issues in visual perception. It has led to the development of a distinction between two levels of stereopsis with the term "global stereopsis"

encompassing percepts produced by random element stereograms and the term "local stereopsis" encompassing percepts produced by conventional Wheatstone stereograms (Julesz, 1971; 1978; Julesz & Schumer, 1981). For research on stereopsis, random element stereograms confer two distinct advantages. First, they provide a purely stereoscopic stimulus that obviates the complications posed by monocular cues. Because the stereoscopic form is contingent upon stereopsis, spatial variables (X- and Y-axes) can be investigated in concert with the depth variable (Z-axis). For these reasons, the random element stereograms are regarded as the optimal method for the present inquiry.

Given the utility of the random element stereogram, the next step is to consider methods of production. Initially, they were produced on computers via software and available only as the hard copy products of printers. Limits on speed of computation precluded real-time generation of the matrices. But advances in electronic technology over the last twenty years have made it possible to generate stereograms in real-time, thereby greatly enhancing their range of application.

The random element stereogram generation system used in this research program sidesteps the speed of computation limit by using high speed, hard-wired logic components. For descriptive purposes, the system can be functionally separated into three units. The first of these is a color video receiver or monitor modified so that the Z-axis of the red and green electron guns can be directly modulated by

external signals. Through such modulation, matrices of randomly generated red and green dots can be generated as the guns sweep the CRT in the raster scan mode. By delaying the on-time of one gun relative to the other, a horizontal difference in the position of dots is produced on the screen, and it is this separation that produces the retinal disparity essential for stereopsis. When an observer views the display while wearing red and green chromatic filter before the eyes, the filters physically segregate the matrices so that each matrix, red or green, stimulates only one eye, thereby fulfilling dichoptic stimulation necessary for stereoscopic presentation. This is the well known anaglyph method of stereoscopic viewing. All elements in the matrices are replaced randomly at a rate of 60 Hz, and this replacement produces a continual apparent motion of the elements reminiscent of Brownian motion or the noise seen on an untuned TV channel. This motion, however, does not impair perceptibility of stereoscopic stimuli and does serve to completely suppress potential monocular cues.

The second unit, the controller, is an electronic device comprised of a network of hard-wired TTL logic components. It generates the random elements and specifies the X-, Y-, Z- coordinates of the stereoscopic stimuli. The temporal duration of the stimuli is controllable in multiples of 16.7 msec, the field rate of the display. The generator alone can produce rectilinear stereoscopic forms of any given dimension. In concert with the third unit described below, stereoscopic forms, both static and kinetic, of virtually any

configuration can be produced.

The third unit, the optical programmer, is a monochrome video camera modified to operate as a flying spot scanner or image digitizer. The scan of the camera is driven by the generator and synchronized with it. The analog signal emitted by the camera as it scans scenes of varying luminance is digitized by the generator. That signal is used to specify the configuration of the target being scanned by the camera. This makes it possible to produce a stereoscopic form identical to the physical target scanned by the camera. In effect, anything scanned by the camera is reproducible in stereoscopic space.

One of the prime advantages offered by this system is the considerable flexibility and ease in stimulus selection. This makes is possible to utilize the sophisticated methodology of contemporary psychophysics and employ such techniques as forced-choice responding in both the spatial and temporal domains. These techniques were used in all the experiments involving threshold estimations, undertaken under this research program.

THEORETICAL ANALYSIS

The conceptual framework underlying the research program derives from the geometrical relationships attendant to stereoscopic depth discrimination. The critical stimulus condition requisite for stereopsis is retinal disparity, which refers to the slightly

different stimulation each eye receives from objects in the world, by virtue of the horizontal separation of the eyes. It is this difference in stimulation that is detected by the visual system and translated into the relative depth percept that characterizes stereoscopic depth perception. The geometrical relationship that produces disparity provides a quantitative index of its magnitude as illustrated in Figure 1 below. In this Figure, all of the convergence of the eyes has been assigned to one eye in the interest of clarity.

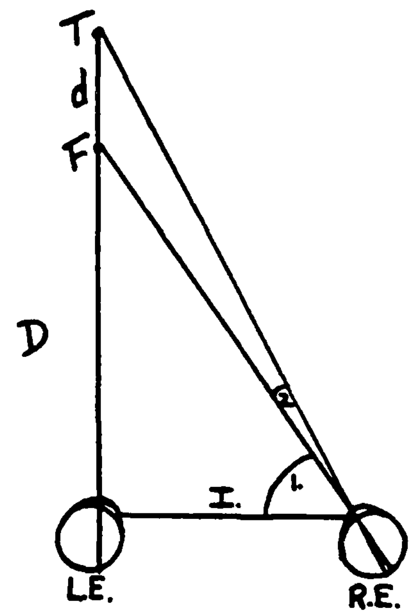

Figure 1.

In the Figure, both eyes fixate a point in space, F, which stimulates corresponding retinal areas in each eye. F is at some

distance, D, from the eyes. A second point, T, is at a greater distance, D + d, from the eyes. The point T stimulates different retinal areas, vis-a-vis the eyes, and is, therefore, retinally disparate. In general, any point that is at a different distance than F, either in front of or behind it, will be disparate. The magnitude of the disparity is the angular difference between the angle that converges on F and the angle that converges on T.

This analysis applies to objects in three-dimensional space where depth is produced by physical differences along the Z-axis. It is of interest, however, that much of what is known about the operating characteristics of stereopsis comes not from research utilizing three-dimensional displays, but rather from two-dimensional displays that simulate or mimic the retinal disparity that would be produced by an object in 3-D space. The two-dimensional simulation is produced by the well-known stereogram, which was devised by Wheatstone in order to demonstrate that sufficiency of retinal disparity as the cue for stereopsis. Although the geometry underlying the construction of stereograms is fundamentally the same as that underlying three-dimensional displays, the computation of disparity and other parameters is somewhat different for stereograms than it is for three-dimensional displays. Further, it is possible to simulate, in stereograms, depth, distances, and disparities that are impossible to produce in true three-dimensional space.

The geometry governing construction of a stereogram is illustrated in Figure 2 below. All points and lines are the

same as in the preceding Figure, except that the horizontal segment S has been added. Line S, which stands for separation, represents the separation between each eye's image that is required to simulate the disparity that would be produced by point d if it was located relative to point F, and both F and d were in true, or physical, three-dimensional space. The angular disparity that S represents is given by S / D in radians when convergence is symmetrical and the

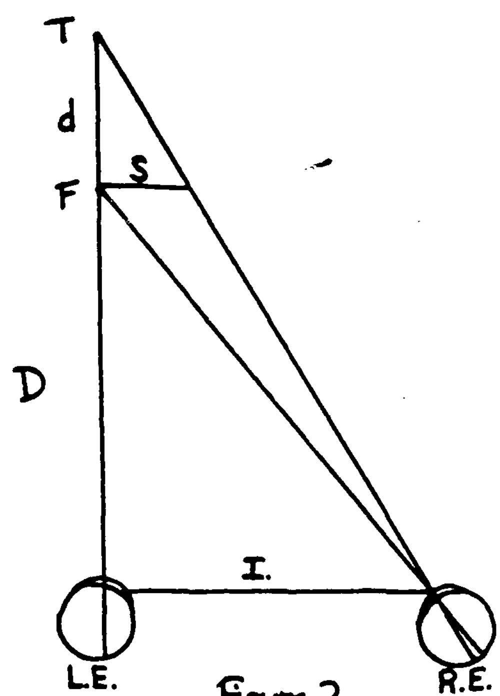

Figure 2.

target is located midway between the eyes and viewed in the frontal parallel plane.

The computation of angular disparity is of interest partially

because a considerable proportion of the research on stereopsis has emphasized detection of disparity and the conditions governing it. Yet, that emphasis has tended to obscure the fact that disparity is a dependent quantity, like the retinal image, that requires, for correct interpretation, information about viewing distance (D). A more important quantity, from most practical conditions of view, is not disparity but, rather, the depth interval (d). When one views a stereoscopic display and observes objects at various depth positions, a question that naturally arises is whether the magnitude of those depth positions is veridical. Veridical can be translated to mean whether the perceived depth magnitudes correspond to those predicted from the geometry of stereopsis.

For stereograms, the computations of those predicted depth intervals is straightforward. In Figures 3, A and B, given below, A represents the conditions for crossed disparity, or front depth, where

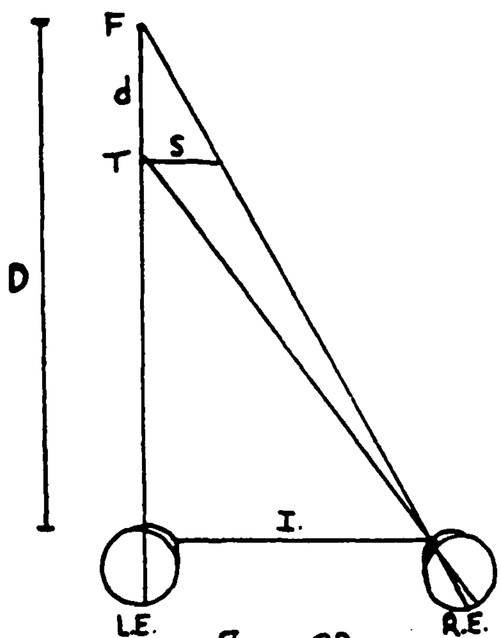

Figure 3A.

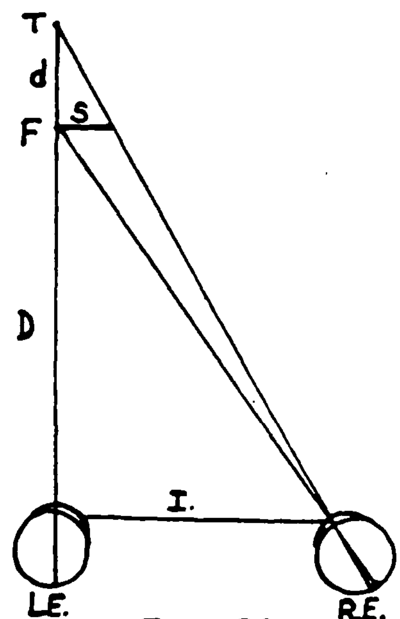

Figure 3B.

the target appears in depth in front of fixation, while B represents the uncrossed disparity case, where the target is behind fixation. As in the previous Figures, D is the distance to fixation, d is the depth interval, I is interpupillary distance, and S is the separation of the stereogram images. In both Figures, A and B, the law of similar triangles applies. Thus, for A, I is to S as (D - d) is to d, and for B, I is to S and (D + d) is to d.

Solving for d yields:

(1) $d = S \times D / I + S$

for crossed disparity and

(2) $d = S \times D / I - S$

for uncrossed disparity.

The extent to which the predicted depth positions of stereoscopic forms corresponds to perceived depth positions is a topic that has received only limited attention in the literature, particularly so for the case where many cues to viewing distance are present, i.e., naturalistic conditions of view. Therefore, many of the the experiments tested, in effect, the predictions inherent in Equations 1 and 2 given above. Note that depth position is a linear function of both viewing distance and disparity as represented by separation. Inspection of Equations 1 and 2 also reveals an

interesting asymmetry in the direction of disparity, crossed and uncrossed. For uncrossed disparity, note that as S increases, depth position (d) becomes positively accelerated and when S = I, depth goes to infinity. Conversely, for crossed disparity, depth is bounded by the distance between fixation and the observer. A more extensive treatment of the computation of depth and disparity for both three-dimensional displays and stereograms can be found in Cormack and Fox (1985; in press).

This analysis of the geometrical relationships underlying stereopsis provided a general framework for guiding the research program. A major objective of the experiments described in the next section was to identify those variables that govern the position of objects in space and to assess their relative strength or weight.

EXPERIMENTAL PROGRAM

In several studies, (Cormack, 1982b; Patterson, Menendez, & Fox, 1982; Fox, Patterson, & Langston, 1983) the effect of variations in viewing distance (distance from observer to the display) and variation in disparity on depth position were examined. The general approach consisted of obtaining, from the observers, estimates of the perceived depth position of a suprathreshold global stereoscopic form seen in a normally illuminated rectilinear room containing the depth cues typical of such an environment. The optimal method of obtaining estimates of perceived depth proved to be alignment, by the observer,

of a probe stimulus with the apparent depth plane of a stereoscopic form. In an impoverished environment containing minimal depth cues this alignment procedure is subject to the criticism that the observer may be simply matching the disparity of the probe with the disparity of the target stimulus, without necessarily registering or taking into account the perceived depth position of the target. This criticism does not apply, however, when the environment contains other depth cues that can be used to calibrate the absolute depth position of the probe stimulus. As noted earlier, such cues were present in the studies. But to be sure that such calibration had occurred the estimates of depth using the probe were supplemented by conventional measures such as magnitude estimation and magnitude production. The excellent agreement among all measures served to validate the probe technique. Observers of varying levels of sophistication and of visual capacity were employed. They all reported that the stereoscopic target was clearly and definitely localized at a fixed position in visual space and all made their judgments rapidly and with confidence. Quantitatively, good agreement was found between the estimates of perceived depth position and those predicted by the geometric model, for both manipulations of disparity and of fixation distance. The outcome was not influenced by either the size or configuration of the stereoscopic target.

When depth judgments are made in environments containing minimal or restricted cues for depth, and multiple targets are present, perceptual interaction among targets occurs and distorts veridical

estimation of depth position. A more salient target can act as a perceptual anchor or magnet that acts to perceptually attract and thus distort the positions of less salient targets. To determine if this interaction would occur under present conditions, estimates of the perceived depth of the target were made in the presence encompassing larger contextual stimulus located in a different depth plane. All manipulations of the contextual stimulus in X-, Y-, and Z-dimensions were ineffective in altering the perceived depth position of the target. In all conditions judgments were veridical.

The failure of context to modify depth position led to examination of a second variable that potentially could be effective in modifying depth position. This variable is the reduction in the number of elements comprising the random element stereogram. When elements are removed from a stereogram, perception of the stereoscopic form is maintained by a filling in process, wherein subjective contours define the edges of the form, a process which compensates for the removal of individual elements. Although the form remains visible under steady state suprathreshold conditions when almost all elements are removed, elements reduction does impair recognition under threshold level conditions. To determine if element reduction influenced depth position, estimation experiments were performed following procedures similar to those described earlier, for stereoscopic targets representing various levels of element reduction. The unequivocal result was that depth position was not influenced even under the severest condition, when only 1% of the elements were

present.

The results of all studies considered so far indicate that perceived depth position of stereoscopic forms corresponds closely to the position predicted from the geometric model of stereopsis. Further, depth position is robust and not modifiable by the potentially perturbing manipulations of context and element density. This conclusion is confined to the restricted range of viewing conditions and disparities that were used to manipulate depth position.

To expand the range of those variables, and in particular viewing distance, in order to provide a more stringent test of the model, a new procedure was devised. This involved inducing a high intensity afterimage with disparity in an observer and then varying the distance between the observer and a fixation or reference point in visual space. Because the disparity of the afterimage is fixed and cannot change in any way, depth position of the projected afterimage relative to fixation distance will increase, in a predictable way, as the distance between the observer and the fixation point is increased. There is essentially no limit on the magnitude of fixation distance because it can be any point in space to which the observer directs visual fixation no matter how distant. For technical reasons, it proved more effective to use depth displays containing real depth, i.e. contours in three-dimensional space, rather than stereograms. Note that in three-dimensional displays, with crossed disparity, the geometry of stereopsis requires that, for smaller distances, depth

position will grow as the square of the fixation distance and then, as distance increases, the function gradually becomes linear with fixation distance. To test predictions about depth position, observers made estimates of the perceived depth position of the stereoscopic images as a function of viewing distance using estimation procedures described previously. The initial experiments were performed indoors using long corridors to provide variations in fixation distance (Cormack, 1981; Cormack, 1982a). To obtain even greater distances, subsequent experiments were performed outdoors, where prominent, distant objects could be used for fixation (Cormack, 1982b; 1984). For all distances, excellent agreement was obtained between the predicted and the perceived depth position of the afterimage targets. This result raises a question about the source of the distance information used by the visual system to compute depth position of the stereoscopic targets. For the longer distances (greater than about 7 meters), the source cannot come from accommodation and convergence because those cues are inoperative at those distances. Rather, the information must comes from the field cues for distance, such as texture and perspective.

Although that conclusion seems inescapable, it is novel in that no relevant prior investigation has employed conditions that would preclude the potential contribution of convergence and accommodation to computation of the distance between the observer and fixation. Further, it has been established that at least when no other depth cues are present, convergence and accommodation can yield distance

information. But these variables, which are sometimes referred to as organismic cues to depth, have not been assessed under naturalistic conditions where many field cues to distance are present. To learn more about the relevant potency of field cues and organismic cues a study was performed in which the two classes of cues were pitted against one another (Cormack & Menendez, 1983). The afterimage technique was used to project disparate targets over short fixation distances in a corridor replete with many depth cues. To manipulate convergence, observers wore prisms that forced them to exert varying degrees of convergence effort in order to maintain fusion. This is a potent manipulation of convergence that has proven to be effective in other situations. But in this instance, convergence was completely ineffective in altering the perceived depth position of the targets. This outcome suggests that information for the computation of fixation distance is derived solely from the field cues to depth. This is an intriguing operation that invites further exploration, but for the present purpose, it is consistent with the conclusion derived from the other experiments, that perceived depth position is veridical when information for fixation distance is available. However, this conclusion is based exclusively on results of experiments in which crossed disparity, or front depth, was employed. That is, the targets appeared in visual space between the display and the observer. The veridicality of the depth position of targets with uncrossed disparity, wherein the target appears to lie in the plane behind the display, has not been examined, although there are grounds for

suspecting the case for targets with uncrossed disparity will differ from that for crossed disparity.

Recall that the geometry of stereopsis predicts an asymmetry in the depth positions of targets with crossed and uncrossed disparity. Targets with crossed disparity are confined to the region between the display and the observer. But the depth positions of targets with uncrossed disparity are ever increasing functions of increases in disparity or viewing distance and, at some point, reach an infinity depth position. This is true for both three-dimensional displays and for the simulation of depth provided by stereograms. With stereograms, however, it is possible to simulate depths that are impossible to obtain in the real three-dimensional world. For instance, any time the separation of the half-images in a stereogram equals or exceeds the interpupillary distance of the observer, the predicted depth position is at, or beyond, infinity. It is not difficult to present targets on a large stereogram, such as one generated by a projection system, with uncrossed disparity that exceeds the theoretical infinity limit. Such targets, however, are clearly perceptible. To learn more about the level of agreement between perceived depth position and that predicted by geometry, an investigation was performed on the relative discriminability of targets with uncrossed disparity some of which exceeded the infinity limit (Fox, Cormack, & Patterson, 1985). All targets were discriminable in depth on an ordinal scale but their absolute depth positions were grossly underestimated. This implies that the capacity

for conveying depth information is constrained considerably for targets with uncrossed disparity relative to the capacity of targets with crossed disparity.

All results discussed so far have implications for the portrayal of stereoscopic or three-dimensional information. An additional factor that bears on the feasibility of three-dimensional displays concerns the degree to which potential operators of such displays are sensitive to stereoscopic information. It had been reported that about 30% of the general population suffers from some deficit or anomaly in stereoscopic depth discrimination. The majority of these anomalies are an insensitivity to the disparity of one sign or another. The selectivity of the anomalies, with respect to disparity sign, inspired the hypothesis that there are separate detectors for the two kinds of disparity, crossed and uncrossed, and that observers who manifest an insensitivity to a particular disparity sign do so because they suffer from a neurologic impairment of one class of detectors. Evidence for that hypothesis, however, comes solely from a particular testing procedure involving discrimination of briefly exposed targets with large disparities. But, investigations of stereoanomaly using different, yet equivalent, methods have not found stereoscopic deficits in a substantial proportion of the population (Fox & Patterson, 1981; Francis, Fox, & Patterson, 1984; Patterson & Fox, 1982; Patterson & Fox, 1984). Rather, the incidence of deficits has been on the order of 1 to 3%, which is consistent with the incidence reported in the ophthalmic literature. This result suggests that

selection of operators would not be a crucial factor in the employment of stereoscopic display systems.

CONCLUSIONS

The implications of the results of this research program for a deeper understanding of stereoscopic depth discrimination and for the design of three-dimensional displays are described below:

1) Stereoscopic targets with crossed disparity are perceived to lie in the depth plane predicted by the geometric model. This veridical perception of depth position holds for all disparities tested and for all conceivable viewing distances. Perceived depth positions are not alterable by perturbing factors in the visual environment. Therefore, targets with crossed disparity are capable of displaying metric information along the Z-axis.

2) The source of the information on fixation distance used by the visual system to compute depth position is not known with certainty but under certain conditions it must include the field cues to distance such as texture gradient and perspective. In terms of practical applications, distance information intrinsic to ordinary environments seems sufficient for computation of depth position.

3) Targets with uncrossed disparity assume depth positions that

do not conform to those predicted from the geometry. It is unlikely that such targets can represent depth information at the level of an interval scale. Rather, it may be possible to represent information only at the level of an ordinal scale. This places constraints on the use of uncrossed disparity in stereoscopic displays.

4) A decision to employ stereoscopic displays need not be conditioned on the assumption that selection of operators will be an impediment. Standard visual screening procedures presently employed should be sufficient.

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REPORTS PREPARED UNDER THIS PROGRAM

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